

1 **WAVEGUIDES ASSEMBLED FOR TRANSVERSE-**
2 **TRANSFER OF OPTICAL POWER**

3 Applicants: Henry A. Blauvelt, David W. Vernooy, Joel S. Paslaski, and Guido
4 Hunziker

5 **RELATED APPLICATIONS**

6 **[0001]** This application claims benefit of the following U. S. provisional applications:

7 **[0002]** App. No. 60/393,974 entitled "Micro-hermetic packaging of optical devices" filed
8 07/05/2002 in the names of Albert M. Benzoni, Henry A. Blauvelt, David W. Vernooy,
9 and Joel S. Paslaski, said provisional application being hereby incorporated by
10 reference as if fully set forth herein; and

11 **[0003]** App. No. 60/466,799 entitled "Low-profile-core and thin-core optical waveguides
12 and methods of fabrication and use thereof" filed 04/29/2003 in the names of David W.
13 Vernooy, Joel S. Paslaski, and Guido Hunziker, said provisional application being
14 hereby incorporated by reference as if fully set forth herein.

15 **BACKGROUND**

16 **[0004]** The field of the present invention relates to optical waveguides. In particular,
17 various adaptations are disclosed herein for facilitating assembly of planar optical
18 waveguides for transverse-transfer of optical power therebetween.

19 **[0005]** This application is related to subject matter disclosed in:

20 **[0006]** U.S. non-provisional App. No. 10/187,030 entitled "Optical junction apparatus
21 and methods employing optical power transverse-transfer" filed 06/28/2002 in the
22 names of Henry A. Blauvelt, Kerry J. Vahala, David W. Vernooy, and Joel S. Paslaski,
23 said application being hereby incorporated by reference as if fully set forth herein;

24 **[0007]** U.S. provisional App. No. 60/360,261 entitled "Alignment-insensitive optical
25 junction apparatus and methods employing adiabatic optical power transfer" filed
26 02/27/2002 in the names of Henry A. Blauvelt, Kerry J. Vahala, David W. Vernooy, and
27 Joel S. Paslaski; and

- 1 **[0008]** U.S. provisional App. No. 60/334,705 entitled "Integrated end-coupled
- 2 transverse-optical-coupling apparatus and methods" filed 10/30/2001 in the names of
- 3 Henry A. Blauvelt, Kerry J. Vahala, Peter C. Sercel, Oskar J. Painter, and Guido
- 4 Hunziker.

SUMMARY

[0009] A first planar optical waveguide includes a first core within lower-index first cladding on a first waveguide substrate. A substantially flat waveguide upper cladding surface is provided over the first core along at least a portion of the length thereof. A second planar optical waveguide includes a second core within lower-index second cladding on a second waveguide substrate. A substantially flat waveguide upper cladding surface is provided over the second core along at least a portion of the length thereof. The first and second planar waveguides are assembled together with at least portions of their corresponding substantially flat waveguide upper cladding surfaces facing one another, thereby positioning the waveguides for transverse-transfer of optical power therebetween along respective transverse-coupled portions of the first and second cores. The waveguide upper cladding surfaces may be positioned against one another upon assembly of the waveguides, or may be spaced apart from one another.

[0010] Additional areas of core material may be provided within the cladding so as to provide corresponding structural upper cladding surfaces in a manner similar to that employed for forming the waveguide upper cladding surfaces. The waveguide and structural upper cladding surfaces are substantially parallel, and may in some instances also be substantially coplanar. The structural upper cladding surfaces are positioned against one another upon assembly of the planar waveguides, thereby providing alignment and/or support.

[0011] Substantially flat waveguide and structural upper cladding surfaces may be formed by deposition of cladding material over a low-profile core, wherein the width of the core (i.e., the lateral dimension) is larger than the height of the core (i.e., the vertical dimension). Alternatively, substantially flat waveguide and structural upper cladding surfaces may be formed by chemical-mechanical polishing (CMP) or other suitable processing of cladding deposited over a core of any shape.

[0012] An embedding or encapsulating medium may be employed for securing the assembled planar waveguides and protecting various optical surfaces thereof. Structural upper cladding surfaces formed by areas of core material may be employed for aiding in the encapsulation process, by providing mechanical alignment and/or

1 support during the embedding process, and/or by directing flow of embedding material
2 precursor(s) to the appropriate locations about the waveguides. Such embedding may
3 serve as a micro-hermetic package and/or may serve to enhance optical
4 properties/performance of the packaged assembled optical waveguides.

5 **[0013]** Objects and advantages pertaining to optical waveguides assembled for
6 transverse-coupling as disclosed herein may become apparent upon referring to the
7 disclosed exemplary embodiments as illustrated in the drawings and disclosed in the
8 following written description and/or claims.

1 BRIEF DESCRIPTION OF THE DRAWINGS

2 **[0014]** Figs. 1A-1E are cross-sectional views of exemplary low-profile-core optical
3 waveguides.

4 **[0015]** Figs. 2A-2E are cross-sectional views of exemplary low-profile-core optical
5 waveguides.

6 **[0016]** Figs. 3A-3C are cross-sectional views of optical waveguides.

7 **[0017]** Figs. 4A-4D are plan and cross-sectional views of assembled optical
8 waveguides.

9 **[0018]** Figs. 5A-5D are cross-sectional and plan views of assembled low-profile-core
10 optical waveguides.

11 **[0019]** Figs. 6-11 illustrate exemplary procedures for forming waveguide and structural
12 upper cladding surfaces.

13 **[0020]** Figs. 12A-12B are longitudinal and transverse cross-sectional views of
14 assembled and embedded low-profile-core optical waveguides.

15 **[0021]** Fig. 13 is a plan view of a low-profile-core optical waveguide.

16 **[0022]** Fig. 14 is a plan view of optical devices assembled onto a waveguide substrate.

17 **[0023]** The embodiments shown in the Figures are exemplary, and should not be
18 construed as limiting the scope of the present disclosure and/or appended
19 claims. It should be noted that the relative sizes and/or proportions of
20 structures shown in the Figures may in some instances be distorted to facilitate
21 illustration of the disclosed embodiments.

DETAILED DESCRIPTION OF EMBODIMENTS

[0024] Low-profile cores as shown in the exemplary waveguides of Figs. 1A-1E and 2A-2E may offer advantages for fabrication and assembly of transverse-coupled optical waveguides. Once the core material layer for a waveguide is deposited and then patterned to form the core, additional cladding material is typically deposited to continue the fabrication process. Deposition processes typically employed exhibit varying degrees of conformality, and when cladding material is deposited over a waveguide core so that the upper cladding thickness and core height are similar (within about a factor of two, for example), a curved cladding upper surface typically results. For a waveguide core with an aspect ratio (width:height) of less than about 2:1, a majority of the upper cladding surface over the waveguide is typically curved (waveguide 1250, core 1252, and cladding 1254 on substrate 1256, as shown in Fig. 3A). In contrast, under similar circumstances a low-profile core (having an aspect ratio greater than about 2:1 (waveguide 1260, core 1262, cladding 1264, and substrate 1266, as shown in Fig. 3B; other examples shown in Figs. 1B and 2B) may typically yield an upper cladding surface curved near the lateral edges of the core but substantially flat above a majority (if not all) of the width of the core. The resulting substantially flat waveguide upper cladding surface may facilitate assembly of the waveguide with another similarly fabricated waveguide with their waveguide upper cladding surfaces facing one another (either against one another, as in Fig. 3C, or spaced-apart from one another). The substantially flat waveguide upper cladding surfaces facilitate stable and reproducible positioning of the waveguides for transverse-transfer of optical power.

[0025] The substantially uniform thickness of material layer(s) deposited to form waveguide core 1262, and substantially uniform deposition processes available for forming cladding 1264 (and the upper surface thereof) provide several advantages. Over short length scales (a few millimeters or less) the portion of the upper cladding surface directly over the waveguide core 1262 (a waveguide upper cladding surface) is substantially flat and uniform, thereby enabling another waveguide 1270 to be positioned on waveguide 1260 against the upper cladding surface and providing reproducible and stable relative positioning of the two waveguide cores, with negligible intervening space between the waveguide upper cladding surfaces (Fig. 3C).

1 Substantial uniformity of deposition over larger length scales (a few centimeters or
2 more) yields multiple substantially identical waveguides 1260 (including substantially
3 identical upper cladding layers) formed concurrently on a common substrate wafer
4 (wafer-scale fabrication). The optical performance of substantially identical waveguides
5 reproducibly and stably positioned for optical transverse-coupling may therefore be
6 relied on for reliable fabrication and assembly of optical devices.

7 **[0026]** Transverse-coupled portions of waveguides 1260 and 1270 of Fig. 3C (as well
8 as transverse-coupled portions of other exemplary waveguides described and/or shown
9 herein) may be adapted for substantially modal-index-matched transverse coupling, or
10 may be adapted for substantially adiabatic transverse-coupling. Such adaptations for
11 transverse-coupling are set forth in detail in earlier-cited App. No. 10/187,030, App. No.
12 60/360,261, and App. No. 60/334,705. One such adaptation for substantially adiabatic
13 coupling is shown in Figs. 4A-4D, which show a core 1112 of a first waveguide tapering
14 down in width until it terminates, while a core 1122 of a second waveguide, transverse-
15 coupled with the first waveguide, originates at a point below core 1112 and tapers up in
16 width as core 1112 tapers down.

17 **[0027]** Figs. 1A-1E show cross sections of exemplary embodiments of a planar optical
18 waveguide including a low-profile core 310. The waveguide is formed on a waveguide
19 substrate 302, typically a substantially planar semiconductor substrate such as silicon.
20 Any suitable waveguide substrate material may be employed, including those listed
21 hereinbelow and equivalents thereof. Core 310 is surrounded by lower-index cladding
22 320. In the examples of Figs. 1A-1E, the waveguide core 310 may comprise a thin
23 layer of silicon nitride (Si_xN_y ; index of about 2) or silicon oxynitride (SiN_xO_y), typically
24 ranging between a few tens and a few hundreds of nanometers in thickness (i.e.,
25 vertical extent). Cladding 320 in this example may comprise silica or doped silica (index
26 around 1.5), so that these exemplary waveguides are high-index-contrast (defined
27 herein as a core/cladding index contrast greater than about 5%). Other suitable high-
28 index-contrast combinations of core and cladding materials may be equivalently
29 employed, including those listed hereinbelow and equivalents thereof.

1 **[0028]** For supporting optical modes at typical telecommunications wavelengths
2 (visible and near-infrared), core 310 of the exemplary high-index-contrast waveguide
3 300 may range between about 0.5 μm and about 8 μm in width (i.e., lateral extent). The
4 particular vertical and lateral extents chosen depend on the desired characteristics of
5 waveguide 300 (described further hereinbelow). A silicon nitride core around 50-100
6 nm high by about 2-3 μm wide (yielding a transverse mode size of around 1-2 μm high
7 by around 1.5-2 μm wide; mode sizes expressed as $1/e^2$ HW intensity) might be well-
8 suited for spatial-mode-matching with a semiconductor optical device mode, while an
9 even thinner (in vertical extent) silicon nitride core around 5-6 μm wide may be well-
10 suited for spatial-mode-matching with larger optical modes, or for facilitating optical
11 transverse-coupling with another waveguide.

12 **[0029]** The cladding 320 between substrate 302 and core 310 may be made
13 sufficiently thick so as to reduce or substantially prevent leakage of optical power from
14 waveguide 300 into substrate 302 (within operationally acceptable limits). A lower
15 cladding thickness greater than about 5 μm , typically greater than about 10 μm , may
16 adequately serve this purpose. In embodiments formed on a silicon or other
17 semiconductor substrate, an oxide buffer layer is sometimes provided on the substrate.
18 Such a buffer layer may comprise the lower cladding, or may comprise an upper surface
19 of the substrate on which the lower cladding is deposited. Other suitable structures may
20 be employed for substantially preventing optical leakage from the waveguide into the
21 substrate while remaining within the scope of the present disclosure and/or claims.

22 **[0030]** The thickness of cladding 320 above core 310 may vary, depending on the
23 intended use of the waveguide. Along portions of the length of the waveguide, the
24 upper cladding may be made sufficiently thick so as to reduce or substantially prevent
25 optical leakage through the upper surface of the waveguide (within operationally
26 acceptable limits), and/or to substantially isolate a supported optical mode from a use
27 environment (within operationally acceptable limits). An upper cladding thickness
28 greater than about 5 μm , typically greater than about 10 μm , may adequately serve this
29 purpose. Along a transverse-coupled portion of the length of the waveguide, a thinner
30 upper cladding layer may be more suitable. Such a thinner upper cladding may typically
31 be less than about 1 μm in vertical extent, and often less than about 0.5 μm in vertical

1 extent, in order to facilitate transverse spatial overlap between optical modes of
2 transverse-coupled waveguides. In other examples, a thin upper cladding layer may be
3 adequate in cases where the waveguide is subsequently embedded or encapsulated in
4 a transparent optical medium having an index less than or about equal to the cladding
5 index. In effect, the embedding medium acts as additional cladding.

6 **[0031]** Depending on the physical and/or mechanical constraints and/or requirements
7 imposed on the waveguide, the cladding 320 may extend laterally away from the core
8 310 so as to reduce or substantially eliminate any effect of a lateral waveguide cladding
9 edge on an optical mode supported by core 310 (as in Figs. 1B and 1E). Alternatively,
10 cladding 320 may be formed so as to yield a protruding lateral surface on one or both
11 sides of core 310 (as in Figs. 1A, 1C, and 1D), and such surface(s) may or may not
12 influence the characteristics of a supported optical mode. Such lateral cladding
13 surfaces may be provided at varying depths, and may or may not extend downward
14 near or beyond the depth of core 310. A waveguide may be formed to include multiple
15 segments having various of these configurations.

16 **[0032]** Additional exemplary embodiments of a planar waveguide including a low-
17 profile core are shown in cross-section in Figs. 2A-2E positioned on a waveguide
18 substrate 402. Substrate 402 may comprise a semiconductor substrate such as silicon
19 (as in the preceding examples), or any suitable substrate material may be employed,
20 including those listed hereinbelow and equivalents thereof. In these examples the
21 waveguide may include a doped silica core 410 within lower-index cladding 420, which
22 may comprise doped or undoped silica. The index contrast is typically much smaller
23 than in the examples of Figs. 1A-1E, and may be less than about 1 or 2%, for example
24 (low-index-contrast, defined herein as core/cladding index contrast less than about 5%).
25 The core may be about 0.5 μm high by about 5 μm wide in this example, yielding a
26 transverse mode size of around 4-5 μm high by around 4-5 μm wide (mode sizes
27 expressed as $1/e^2$ HW intensity). Such a mode might be well-suited for spatial-mode-
28 matching with an optical fiber mode. A low-profile, low-index-contrast waveguide core
29 may range from about 0.3 μm high up to about 2-3 μm high, and between about 1 μm
30 and about 10 μm wide. Specific combinations of dimensions will depend on the desired
31 spatial mode characteristics and the particular degree of index contrast employed. In

1 addition to doped and undoped silica, other suitable low-index-contrast combinations of
2 core and cladding materials may be equivalently employed, including those listed
3 hereinbelow and equivalents thereof.

4 **[0033]** As in the previous examples, cladding 420 below core 410 may be sufficiently
5 thick so as to reduce or substantially eliminate optical leakage from waveguide 400 into
6 substrate 402 (within operationally acceptable limits), alone or in combination with a
7 buffer layer provided on the substrate. Upper cladding may be sufficiently thick along
8 portions of the waveguide so as to substantially prevent optical leakage through the
9 upper surface of the waveguide, and/or may be sufficiently thin along other portions of
10 the length of the waveguide so as to facilitate optical transverse-coupling between
11 waveguides. Lateral portions of cladding 420 may be configured in any of the various
12 ways described hereinabove, and waveguide 400 may be formed to include multiple
13 segments having various of these configurations.

14 **[0034]** The structural properties of the layers and spatially selective material
15 processing steps used to form a waveguide with a low-profile core may be further
16 exploited for forming nearby structural members for alignment and/or support of optical
17 waveguides assembled for transverse-coupling. In Figs. 5A, 5B, and 5D, a pair of
18 elongated areas 1330 of core material are shown on either side of core 1310, all
19 patterned from a common layer of core material deposited on a lower layer of cladding
20 1320 on substrate 1302. Additional areas 1340 may be similarly patterned from the
21 core material layer. Since core 1310 and structural areas 1330 and 1340 are formed
22 concurrently from the same core material layer, their respective upper surfaces are
23 substantially coplanar. Deposition of additional cladding 1320 yields substantially flat
24 areas of the upper cladding surface of waveguide 1300 (above core 1310, forming a
25 waveguide upper cladding surface) and above areas 1330 and 1340 (forming structural
26 upper cladding surfaces). These respective upper cladding surfaces are substantially
27 coplanar, and thus yield an enlarged mechanical mating surface for another similarly
28 adapted waveguide 1350 (including core 1351, cladding 1352, and structural areas
29 1353 and 1354 on substrate 1355 along with optical device 1356; shown in Figs. 5A,
30 5C, and 5D) assembled therewith for optical transverse-coupling. The enlarged contact
31 surface area between the assembled waveguides reduces the likelihood of mechanical

1 damage to the waveguides during positioning, alignment, and bonding (compression,
2 thermal, soldering, or otherwise) and provides more stable and reproducible positioning
3 relative to assembled waveguides lacking such enlarged areas of mechanical contact.
4 Patterning of the structural members 1330/1340 from the same layer as the waveguide
5 core 1310 (and subsequent concurrent deposition of cladding material 1320 over all)
6 results in structural surfaces that are well aligned with respect to the relevant optical
7 surfaces. Similarly, patterning of structural members 1353/1354 from the same layer as
8 the waveguide core 1351 (and subsequent concurrent deposition of cladding 1352 over
9 all) similarly results in structural surfaces that are well aligned with respect to the
10 relevant optical surfaces.

11 **[0035]** The outlying structural areas 1340/1354 may be disposed about the waveguide
12 cores 1310/1351, respectively, so as to provide additional alignment and/or support for
13 the assembled substrates and to facilitate manipulation and placement of substrate
14 1355 on substrate 1302 (for assembling together the waveguides for transverse-
15 coupling). Fig. 5D shows an outline of substrate 1355 (along with corresponding
16 waveguide core 1351 and alignment/support structural members 1353/1354) positioned
17 over substrate 1302. An outline or "footprint" 1359 for a device used to handle
18 substrate 1355 is also shown. If the outlying alignment/support structural members
19 1340/1354 are positioned sufficiently far apart, non-parallelism of substrates 1302 and
20 1352 will not cause further tilting of the substrates relative to one another (and possible
21 separation of the substrates at one edge), but will rather result in the substrates being
22 forced together into a substantially parallel arrangement with the respective structural
23 upper cladding surfaces positioned against one another. The substrates 1302 and 1355
24 may be further provided with metal solder contact areas and/or solder pads (not shown).
25 These may be arranged so as to make first contact as the substrates are brought
26 together for assembly. Heating the solder to its reflow temperature enables the
27 substrates to further settle toward one another, until the respective structural upper
28 cladding surfaces make contact. The solder is then allowed to cool and solidify with the
29 substrates held in this fully engaged position.

30 **[0036]** Exemplary dimensions and positions that might be employed for forming
31 waveguide core 1310 and alignment/support structural members 1330 may be about 6

1 μm wide for core 1310 and structural members 1330 (formed from a silicon nitride layer
2 about 50-100 nm thick in this example), with about a 9 μm separation between the core
3 and the adjacent structural members. Corresponding exemplary dimensions for
4 structures on substrate 1355 may be about 2 μm for waveguide core 1351 and about 10
5 μm wide for alignment/support structural members 1353 (formed from a silicon nitride
6 layer about 50-100 nm thick in this example), with about a 9 μm gap between the
7 waveguide core and adjacent structural members. The greater width of waveguide core
8 1310 relative to waveguide core 1351 yields a broader range of lateral positions over
9 which an operationally acceptable level of optical transverse-coupling may be achieved,
10 while the greater widths of structural members 1353 relative to structural members 1330
11 yields a correspondingly larger range of lateral positions over which adequate
12 mechanical engagement is maintained. In particular, there may be instances wherein
13 operationally acceptable optical transverse-coupling might be achieved with negligible
14 (or only oblique) mechanical contact between waveguide upper cladding surfaces. In
15 such instances, contact between the structural upper cladding surfaces provides the
16 needed mechanical alignment and support, despite a substantial lack thereof near the
17 waveguide cores. Many suitable sets of number, shapes, positions, and/or dimensions
18 for various alignment and/or support structural members may be employed (in addition
19 to exemplary configurations set forth herein), depending on the optical and/or
20 mechanical characteristics desired for the assembled transverse-coupled waveguides.

21 **[0037]** The structural members 1330 should be far enough from core 1310 to
22 substantially avoid (within operationally acceptable limits) optical transverse-coupling
23 therewith, and to similarly substantially avoid optical transverse-coupling with waveguide
24 core 1351 upon assembly (over a range of relative waveguide positions within the
25 assembly tolerance). Analogously, structural members 1353 should be far enough from
26 core 1351 to substantially avoid (within operationally acceptable limits) optical coupling
27 therewith, and to similarly substantially avoid optical coupling with waveguide core 1310
28 upon assembly (over a range of relative waveguide positions within the assembly
29 tolerance). Separation between a waveguide core and an adjacent elongated structural
30 member greater than about the width of the waveguide core may prove sufficient in may
31 circumstances.

1 **[0038]** Various material processing sequences and/or techniques may be employed for
2 forming substantially flat waveguide and structural upper cladding surfaces. In a first
3 exemplary procedure (Fig. 6), cladding material 620 may be deposited over a portion of
4 the substrate and lower cladding that includes at least a portion of core area 610 and
5 structural member areas 630 of the core material layer. Cladding material 620 is
6 deposited to the thickness desired for cladding material above the area(s) of core
7 material, once the core material layer is deposited and the desired areas 610 and 630
8 have been patterned. The resulting waveguide and structural upper cladding surfaces
9 are substantially coplanar, and assembly of two such waveguides results in both
10 waveguide and structural upper cladding surfaces being positioned against one another.
11 Another exemplary procedure (Fig. 7) may be employed if thicker areas of cladding
12 material are desired elsewhere on the substrate. A thicker cladding layer 720 may be
13 deposited over the substrate, followed by spatially-selective etching of the area
14 encompassing the structural areas 730 and at least a portion of the core area 710 of the
15 patterned core material layer. Both the deposition and etch processes tend to preserve
16 the surface topography of the patterned areas of core material. The final thickness of
17 cladding above the patterned core material (and therefore the height of the waveguide
18 and structural upper cladding surfaces) is determined in part by timing the etch process,
19 which may or may not be sufficiently precise depending on the relevant operationally
20 acceptable parameters.

21 **[0039]** Another exemplary procedure may be employed (Fig. 8) in which upper
22 cladding material 820 is first deposited to the thickness desired for the waveguide and
23 structural upper cladding. A first etch-stop layer of any suitable type is deposited and
24 patterned so as to cover the structural core material areas 830 (etch-stop areas 831)
25 and at least a portion of the waveguide core area 810 (etch-stop area 811). Additional
26 cladding material 820 is then deposited over the substrate to the thickness desired for
27 other areas of the substrate, covering the etch-stop areas 811 and 831. A second etch-
28 stop layer 821 of any suitable type is deposited and patterned so as to expose the
29 cladding above the etch-stop layer areas 811 and 831, but protecting areas where
30 thicker cladding is desired. The entire substrate is then subjected to a suitable etch
31 process, which stops at the respective etch-stop layers. After removal of the (now

1 exposed) etch-stop layers, the desired waveguide and structural upper cladding
2 surfaces are ready for assembly with another waveguide 850 for transverse-coupling.
3 The structures produced by the procedures of Figs. 7 and 8 produce similar waveguides
4 and structural members, but the procedure of Fig. 8 may offer greater precision for
5 achieving a desired upper cladding thickness for the waveguide core and structural
6 members.

7 **[0040]** Each of the foregoing exemplary processes yields substantially coplanar
8 waveguide and structural upper cladding surfaces, so that upon assembly for
9 transverse-coupling both waveguide and structural member upper cladding surfaces are
10 positioned against their counterparts on the other similarly adapted waveguide
11 substrate. This may typically be a suitable arrangement. There may be instances,
12 however, where it is desirable to assemble waveguides for transverse-transfer of optical
13 power therebetween while leaving a gap between the facing waveguide upper cladding
14 surfaces (typically on the order of one or a few tenths of a micron). The procedures of
15 Figs. 7 and 8 may each be adapted to yield substantially parallel waveguide and
16 structural upper cladding surfaces that differ in height above the substrate. In an
17 exemplary adaptation of the procedure of Fig. 7, an additional etch step may be
18 performed restricted to an area above core 710, thereby producing a waveguide upper
19 cladding surface lower than the structural upper cladding surfaces. The height
20 difference may be determined through control of etch parameters employed. Similarly,
21 Fig. 8 may be adapted by employing an additional etch step restricted to an area above
22 core 810 (after selective removal of etch-stop layer 811, for example).

23 **[0041]** In the procedure of Fig. 9, after patterning of the core material layer to form the
24 core area 910 and structural areas 930, cladding material 920 is deposited over the
25 substrate to the thickness desired for the waveguide upper cladding. A suitable etch-
26 stop layer 911 is deposited and patterned to cover a portion of the core area 910 only.
27 Additional cladding 920 is then deposited over the substrate (covering the first etch-stop
28 layer 911) to the thickness desired for the structural member upper cladding. A second
29 etch-stop layer 931 is deposited and patterned to cover only the structural member
30 areas 930. Additional cladding 920 is then deposited over the substrate (covering the
31 second etch-stop layer 931) to the thickness desired for the remainder of the substrate,

1 and a third etch-stop layer 921 is deposited covering those areas where thicker cladding
2 is desired (but leaving exposed the desired areas of cladding above the first and second
3 etch-stop layers). The entire substrate is then subjected to a suitable etch process,
4 which stops at the etch-stop layers over each respective area. After removal of the
5 etch-stop layers, the desired waveguide and structural upper cladding surfaces are
6 ready for assembly with another waveguide 950 for transverse-coupling. The structural
7 upper cladding surfaces (above areas 930), being higher than the waveguide upper
8 cladding surface, may be positioned against their counterpart areas on another
9 waveguide substrate while leaving a gap between the facing waveguide upper cladding
10 surfaces of the assembled transverse-coupled waveguides.

11 **[0042]** It should be noted that the foregoing procedures are exemplary. Many other
12 material processing sequences or procedures may be contrived to produce waveguide
13 and structural upper cladding surfaces while remaining within the scope of the present
14 disclosure and/or appended claims.

15 **[0043]** Each of the foregoing exemplary processes depends at one or more stages on
16 substantially flat cladding material surfaces being formed by deposition over a low-
17 profile waveguide core. In contrast, chemical-mechanical polishing (CMP) and/or
18 equivalent processing technique(s) may be employed to produce substantially flat
19 waveguide and structural upper cladding surfaces, regardless of the topography of the
20 underlying core material. While deposition of cladding material over a low-profile core
21 may typically result in waveguide structures resembling Figs. 1B and 2B, for example,
22 CMP may be employed to produce the waveguide structures resembling Figs. 1E and
23 2E, for example. CMP and/or equivalent processes may be employed to produce
24 substantially flat substantially coplanar waveguide and structural upper cladding
25 surfaces, for a low-profile core area 998 (Fig. 10A) as well as for a core area 999 having
26 a height comparable to or even greater than its thickness (Fig. 10B). CMP may be
27 employed to yield separate waveguide and structural member surfaces similar to those
28 described hereinabove over structural area 996 and core area 997 of a patterned core
29 material layer (middle step of Fig. 11), or may be carried further to yield a single
30 substantially contiguous substantially flat surface over both waveguide core and
31 structural areas (last step of Fig. 11). Such a single flat surface may be assembled with

1 another similarly configured waveguide substrate, or may be assembled with a
2 substrate having separate waveguide and structural upper cladding areas (such as
3 waveguide 1350 of Fig. 5A, for example).

4 **[0044]** Transparent embedding media are frequently employed for securing assembled
5 optical components together and to provide a mechanical/moisture/chemical barrier for
6 isolating critical optical surfaces from contamination or damage. Such embedding
7 media may fulfill the function of more traditional hermetic packaging, and may frequently
8 take the form of polymer precursors that are applied to an optical assembly in liquid
9 form, allowed to flow into and fill the desired volumes in and around the optical
10 assembly, and then cured to form a substantially solid embedding medium surrounding
11 the assembled optical components. Such embedding may also serve to reduce the
12 index contrast between various components of the optical assembly and the
13 surrounding environment. Reduced index contrast may serve to: reduce unwanted
14 reflections at transmissive component surfaces; reduce optical scattering and/or
15 unwanted optical coupling due to imperfect or irregular component surfaces; reduce
16 diffractive losses for an optical waveguide end-coupled with another optical waveguide,
17 component, or device; loosen translational and/or angular alignment tolerances for
18 transverse-coupled or end-coupled optical components; and/or reduce optical losses
19 and/or unwanted optical coupling due to mechanical juxtaposition of transverse-coupled
20 optical components. An exemplary optical assembly is shown in Figs. 12A-12B
21 including transverse-coupled optical waveguides 1600 (including core 1610, cladding
22 1620, and support members 1630 on substrate 1602) and 1700 (including core 1710,
23 cladding 1720, and support members 1730 on substrate 1702; waveguide 1700
24 integrated and end-coupled with optical device 1704). Waveguide 1700 terminates at
25 end face 1701, while waveguide 1600 terminates at end face 1601. Along the
26 waveguide segments where optical transverse-coupling occurs, cores 1610 and 1710
27 are each provided with relatively thin upper cladding (cladding 1620 and 1720,
28 respectively; typically less than 1 μm thick). The thin upper cladding makes the
29 respective cores accessible for transverse-coupling. Unacceptable levels of optical
30 loss and/or undesirable optical mode coupling may be induced: i) in waveguide 1700 by
31 device end face 1703; ii) in waveguide 1700 by the abrupt appearance of waveguide

1600 at end face 1601; iii) in waveguide 1600 by the abrupt appearance of waveguide 1700 at end face 1701; iv) in waveguide 1600 by the abrupt appearance of a thicker upper cladding layer at face 1603. Surface irregularities and/or contamination along the sides and/or exposed surfaces of waveguides 1600 and/or 1700 may also lead to unacceptable levels of optical loss and/or undesirable optical mode coupling. Filling spaces 1801, 1802, 1803, and 1804 with an embedding medium having an index near that of cladding 1620 and/or 1720 (or at least nearer than an index of unity) serves to reduce such optical losses and mode couplings. If the embedding material index substantially matches that of cladding 1620 and 1720, losses and mode coupling from these sources may be substantially eliminated.

[0045] To have the desired effect, an embedding medium must cover substantially uniformly the relevant optical surfaces. If the coverage is non-uniform, optical losses and/or undesirable optical mode couplings may not be sufficiently reduced, and may even be increased relative to a non-embedded optical assembly. Substantially uniformly filling volumes 1803 and 1804 may prove problematic, due to the elongated shape and relatively thin vertical extent (less than 0.5 μm for silicon nitride cores 1610 and 1710, for example). Surface tension and/or viscosity of the embedding precursor, as well as air trapped within these volumes, may not always result in uniform filling of volumes 1803/1804. Support structures 1630 and/or 1730 may be segmented (as in Fig. 13), leaving lateral channels 1805 between the support structure segments. These lateral channels provide multiple flow paths (indicated by arrows) for embedding precursor to substantially fill all of the required volumes 1803 and 1804, while also providing a path for air to escape as the embedding material flows in. Flow channels of differing depths may be employed for controlling the flow of embedding material. For example, a deeper longitudinal channel 1806 may provide rapid flow, so that slower flow through lateral channels 1805 flows in the same direction for all such channels. Such unidirectional flow may result in more uniform filling of volumes 1803/1804. Support structures on both of the assembled waveguide substrates may be segmented in this way, or on only one or the other of the assembled waveguide substrates. It may be desirable to provide additional structures (not shown) similar to support structures 1630/1730 on one or both of substrates 1602 and 1702 near the respective

1 waveguides, not necessarily to provide additional mechanical support, but to further
2 guide the flow of embedding precursor on the optical assembly (directing flow in some
3 instances, diverting or preventing flow in other instances).

4 **[0046]** Additional structures may be employed elsewhere on a waveguide substrate for
5 guiding the flow of embedding material precursor prior to curing. Fig. 14 shows a
6 waveguide substrate 1902 with waveguides 1900 and optical devices 1910 assembled
7 onto substrate 1902. Concealed beneath devices 1910 are optical transverse-coupled
8 waveguides and support structures as shown in Figs. 12A-12B and Fig. 13 (including
9 segmented support structures for facilitating embedding precursor flow around the
10 waveguides). Also shown is a gutter 1920 formed around the optical assembly, for
11 limiting the extent of the flow of the embedding precursor. Excess precursor would flow
12 into the gutter, either to remain there or to flow off of the substrate wafer, through saw
13 cut 1922 in this example. Structures 1930, similar in form to support structures
14 1630/1640 of Figs. 12A-12B and Fig. 13, are shown limiting precursor flow near one of
15 devices 1910. Such gutters and barriers may be configured in a variety of ways for
16 meeting particular structural requirements for the location of embedding material, while
17 remaining within the scope of the present disclosure and/or appended claims.

18 **[0047]** It should be noted that such embedding flow control structures, as with other
19 structures formed on substrate 1902, may be formed using spatially selective material
20 processing on a wafer scale concurrently for many substrates 1902. Assembly of
21 components 1910 onto substrate 1902 may be performed on a wafer scale for multiple
22 substrates 1902 prior to division of the wafer, or such assembly may be performed after
23 division of the wafer (either at the "bar" level for multiple substrates 1902 in single rows
24 divided from the wafer, or at the individual substrate level). If assembly is performed
25 prior to division of the wafer or at the bar level, then application of embedding precursor
26 to substrate 1902 and assembled components 1902 may also be performed prior to
27 division of the substrate wafer or at the bar level, respectively.

28 **[0048]** A variety of optical waveguides, optical devices, and/or optical components may
29 be secured and embedded on a planar waveguide substrate as described hereinabove.
30 Embedded optical components and/or waveguides may be transverse-coupled, end-

1 coupled, or otherwise arranged for achieving the desired optical functionality.
2 Embedding of such components and/or waveguides shall fall within the scope of the
3 present disclosure and/or appended claims.

4 **[0049]** There are many suitable materials that may be employed for embedding optical
5 waveguides and other optical components and/or devices on a planar waveguide
6 substrate. Silicone and silicone-based polymer of various sorts have been successfully
7 employed for such embedding. Other suitable materials may include but are not limited
8 to polyimides, epoxies, CYTOP (Asahi Glass Company; a poly-fluorinated polymeric
9 material that may be cross-linked), silicone and silicone-based polymers, siloxane
10 polymers, CycloteneTM (B-staged bis-benzocyclobutene, Dow), Teflon® AF (DuPont), or
11 other polymers. Various of these materials may have significantly temperature-
12 dependent refractive indices. If such materials are employed, this temperature
13 dependency must be compensated in some instances, may be exploited in other
14 instances for active device control, or may be safely ignored in still other instances.

15 **[0050]** For purposes of the foregoing written description and/or the appended claims,
16 "index" may denote the bulk refractive index of a particular material (also referred to
17 herein as a "material index") or may denote an "effective index" n_{eff} , related to the
18 propagation constant β of a particular optical mode in a particular optical element by $\beta =$
19 $2\pi n_{eff}/\lambda$. The effective index may also be referred to herein as a "modal index". As
20 referred to herein, the term "low-index" shall denote any materials and/or optical
21 structures having an index less than about 2.5, while "high-index" shall denote any
22 materials and/or structures having an index greater than about 2.5. Within these
23 bounds, "low-index" may refer to: silica (SiO_x), germano-silicate, boro-silicate, other
24 doped silicas, and/or other silica-based materials; silicon nitride (Si_xN_y) and/or silicon
25 oxynitrides (SiO_xN_y); other glasses; other oxides; various polymers; and/or any other
26 suitable optical materials having indices below about 2.5. "Low-index" may also include
27 optical fiber, optical waveguides, planar optical waveguides, and/or any other optical
28 components incorporating such materials and/or exhibiting a modal index below about
29 2.5. Similarly, "high-index" may refer to materials such as semiconductors, IR materials,
30 and/or any other suitable optical materials having indices greater than about 2.5, and/or
31 optical waveguides of any suitable type incorporating such material and/or exhibiting a

1 modal index greater than about 2.5. The terms "low-index" and "high-index" are to be
2 distinguished from the terms "lower-index" and "higher-index", also employed herein.
3 "Low-index" and "high-index" refer to an absolute numerical value of the index (greater
4 than or less than about 2.5), while "lower-index" and "higher-index" are relative terms
5 indicating which of two particular materials has the larger index, regardless of the
6 absolute numerical values of the indices.

7 **[0051]** For purposes of the foregoing written description and/or the appended claims,
8 the term "optical waveguide" (or equivalently, "waveguide") as employed herein shall
9 denote a structure adapted for supporting one or more optical modes. Such
10 waveguides shall typically provide confinement of a supported optical mode in two
11 transverse dimensions while allowing propagation along a longitudinal dimension. The
12 transverse and longitudinal dimensions/directions shall be defined locally for a curved
13 waveguide; the absolute orientations of the transverse and longitudinal dimensions may
14 therefore vary along the length of a curvilinear waveguide, for example. Examples of
15 optical waveguides may include, without being limited to, various types of optical fiber
16 and various types of planar waveguides. The term "planar optical waveguide" (or
17 equivalently, "planar waveguide") as employed herein shall denote any optical
18 waveguide that is provided on a substantially planar substrate. The longitudinal
19 dimension (i.e., the propagation dimension) shall be considered substantially parallel to
20 the substrate. A transverse dimension substantially parallel to the substrate may be
21 referred to as a lateral or horizontal dimension, while a transverse dimension
22 substantially perpendicular to the substrate may be referred to as a vertical dimension.
23 Examples of such waveguides include ridge waveguides, buried waveguides,
24 semiconductor waveguides, other high-index waveguides ("high-index" being above
25 about 2.5), silica-based waveguides, polymer waveguides, other low-index waveguides
26 ("low-index" being below about 2.5), core/clad type waveguides, multi-layer reflector
27 (MLR) waveguides, metal-clad waveguides, air-guided waveguides, vacuum-guided
28 waveguides, photonic crystal-based or photonic bandgap-based waveguides,
29 waveguides incorporating electro-optic (EO) and/or electro-absorptive (EA) materials,
30 waveguides incorporating non-linear-optical (NLO) materials, and myriad other
31 examples not explicitly set forth herein which may nevertheless fall within the scope of

1 the present disclosure and/or appended claims. Many suitable substrate materials may
2 be employed, including semiconductor, crystalline, silica or silica-based, other glasses,
3 ceramic, metal, and myriad other examples not explicitly set forth herein which may
4 nevertheless fall within the scope of the present disclosure and/or appended claims.

5 **[0052]** One exemplary type of planar optical waveguide that may be suitable for use
6 with optical components disclosed herein is a so-called PLC waveguide (Planar
7 Lightwave Circuit). Such waveguides typically comprise silica or silica-based
8 waveguides (often ridge or buried waveguides; other waveguide configuration may also
9 be employed) supported on a substantially planar silicon substrate (typically with an
10 interposed silica or silica-based optical buffer layer). Sets of one or more such
11 waveguides may be referred to as planar waveguide circuits, optical integrated circuits,
12 or opto-electronic integrated circuits. A PLC substrate with one or more PLC
13 waveguides may be readily adapted for mounting one or more optical sources, lasers,
14 modulators, and/or other optical devices adapted for end-transfer of optical power with a
15 suitably adapted PLC waveguide. A PLC substrate with one or more PLC waveguides
16 may be readily adapted (according to the teachings of earlier-cited U.S. App. No.
17 60/334,705, U.S. App. No. 60/360,261, U.S. App. No. 10/187,030, and/or U.S. App. No.
18 60/466,799) for mounting one or more optical sources, lasers, modulators, and/or other
19 optical devices adapted for transverse-transfer of optical power with a suitably adapted
20 PLC waveguide (mode-interference-coupled, or substantially adiabatic, transverse-
21 transfer; also referred to as transverse-coupling).

22 **[0053]** For purposes of the foregoing written description and/or appended claims,
23 "spatially-selective material processing techniques" shall encompass epitaxy, layer
24 growth, lithography, photolithography, evaporative deposition, sputtering, vapor
25 deposition, chemical vapor deposition, beam deposition, beam-assisted deposition, ion
26 beam deposition, ion-beam-assisted deposition, plasma-assisted deposition, wet
27 etching, dry etching, ion etching (including reactive ion etching), ion milling, laser
28 machining, spin deposition, spray-on deposition, electrochemical plating or deposition,
29 electroless plating, photo-resists, UV curing and/or densification, micro-machining using
30 precision saws and/or other mechanical cutting/shaping tools, selective metallization
31 and/or solder deposition, chemical-mechanical polishing for planarizing, any other

1 suitable spatially-selective material processing techniques, combinations thereof, and/or
2 functional equivalents thereof. In particular, it should be noted that any step involving
3 “spatially-selectively providing” a layer or structure may involve either or both of:
4 spatially-selective deposition and/or growth, or substantially uniform deposition and/or
5 growth (over a given area) followed by spatially-selective removal. Any spatially-
6 selective deposition, removal, or other process may be a so-called direct-write process,
7 or may be a masked process. It should be noted that any “layer” referred to herein may
8 comprise a substantially homogeneous material layer, or may comprise an
9 inhomogeneous set of one or more material sub-layers. Spatially-selective material
10 processing techniques may be implemented on a wafer scale for simultaneous
11 fabrication/processing of multiple structures on a common substrate wafer.

12 **[0054]** It should be noted that various components, elements, structures, and/or layers
13 described herein as “secured to”, “connected to”, “deposited on”, “formed on”, or
14 “positioned on” a substrate may make direct contact with the substrate material, or may
15 make contact with one or more layer(s) and/or other intermediate structure(s) already
16 present on the substrate, and may therefore be indirectly “secured to”, etc, the
17 substrate.

18 **[0055]** The phrase “operationally acceptable” appears herein describing levels of
19 various performance parameters of optical components and/or optical devices, such as
20 optical power transfer efficiency (equivalently, optical coupling efficiency), optical loss,
21 undesirable optical mode coupling, and so on. An operationally acceptable level may
22 be determined by any relevant set or subset of applicable constraints and/or
23 requirements arising from the performance, fabrication, device yield, assembly, testing,
24 availability, cost, supply, demand, and/or other factors surrounding the manufacture,
25 deployment, and/or use of a particular optical device. Such “operationally acceptable”
26 levels of such parameters may therefor vary within a given class of devices depending
27 on such constraints and/or requirements. For example, a lower optical coupling
28 efficiency may be an acceptable trade-off for achieving lower device fabrication costs in
29 some instances, while higher optical coupling may be required in other instances in
30 spite of higher fabrication costs. The “operationally acceptable” coupling efficiency
31 therefore varies between the instances. In another example, higher optical loss (due to

1 scattering, absorption, undesirable optical coupling, and so on) may be an acceptable
2 trade-off for achieving lower device fabrication cost or smaller device size in some
3 instances, while lower optical loss may be required in other instances in spite of higher
4 fabrication costs and/or larger device size. The “operationally acceptable” level of
5 optical loss therefore varies between the instances. Many other examples of such
6 trade-offs may be imagined. Optical devices and fabrication methods therefor as
7 disclosed herein, and equivalents thereof, may therefore be implemented within
8 tolerances of varying precision depending on such “operationally acceptable”
9 constraints and/or requirements. Phrases such as “substantially adiabatic”,
10 “substantially spatial-mode-matched”, “substantially modal-index-matched”, “so as to
11 substantially avoid undesirable optical coupling”, and so on as used herein shall be
12 construed in light of this notion of “operationally acceptable” performance.

13 **[0056]** While particular examples have been disclosed herein employing specific
14 materials and/or material combinations and having particular dimensions and
15 configurations, it should be understood that many materials and/or material
16 combinations may be employed in any of a variety of dimensions and/or configurations
17 while remaining within the scope of inventive concepts disclosed and/or claimed herein.

18 **[0057]** It is intended that equivalents of the disclosed exemplary embodiments and
19 methods shall fall within the scope of the present disclosure and/or appended claims. It
20 is intended that the disclosed exemplary embodiments and methods, and equivalents
21 thereof, may be modified while remaining within the scope of the present disclosure
22 and/or appended claims.